



Swarming Unmanned Aircraft Systems

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Executive Summary

Problem Definition The Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) Unmanned Systems Office looks beyond next generation systems to determine what capabilities and systems may become a viable part of strategy and tactics in the future. Specific to Unmanned Aircraft Systems (UAS), they see a strong and central role for them in the future, post Future Combat Systems (FCS). Based on assumptions about advancement of data transmission, stealth capability, and computational power, AMRDEC wants to maximize the UAV's effectiveness.

One method is to establish a more direct link between operational users and the system itself. They do not want to limit direct access to only Military Occupational Specialty (MOS) trained UAS operators. Rather, they feel that opportunities will exist that will allow any soldier in the battle space to employ one or more Unmanned Aerial Vehicles (UAVs) for a specific task during a specific time and still effectively execute the duties of their primary MOS. This can be done by embedding Semi-Autonomous and Self-Collaborating (SASC) characteristics within swarms of UAS that support operations.

Technical Approach The approach taken to model this system begins with an examination of the state of the art. Since the inception of the Global War on Terror (GWOT), UAS use has climbed dramatically each year, over 300,000 hours in fiscal year 2007 alone. US Army UAV operators have the ability to generate routes and Areas of Interest (AOI) for the UAS to fly to. Soon they will be able to control up to 4 different UAV from the same location. However, the UAVs still require specific mission planning and dedicated payload operators in order to acquire and identify targets. AMRDEC is looking to SASC UAS that can support multiple craft in a bounded area in order to, for instance, conduct reconnaissance.

The approach is comprised of three parts; stakeholder analysis, designing the system, and simulating the UAS behavior.

1) **Stakeholder Analysis.** Speak to UAS operators and determine what capabilities they think the system would need to become SASC. Have them provide their proposed improvements.

2) **System Design.** Assume that an infantry Soldier needs the service of UAS to improve their intelligence picture. They could draw from a bank of UAS standing by. The few that are chosen to help him are given the coordinates of the AOI, a doctrinal task, and a list of "interesting" items to search for. His new recon team forms a loose network in order to collaborate. When one or more UAVs spot an "interesting" item, they contact the Soldier and track the object until told to continue with the search. Meanwhile the other UAVs take up the slack in the AOI left by UAVs holding over targets. Though this system seems complex, it can be managed with a few simple rules.

With simplicity in mind, I examined systems of collaborating entities, specifically insects and animals. Individual UAVs will not have a global operating picture yet they must work in concert with other UAVs to execute a collective task. One method to drive organized behavior is employment of pheromones.

Ants, when foraging, leave a trail of pheromones in their wake. They search for food stores close to their colony. When an ant finds a food source, it traverses back and forth from the food to the colony with its treasure. Other ants sense the higher concentration of pheromone along the successful ant's trail and are drawn to it. They too find food and also strengthen the scent of the trail. This scheme gets the most ants to the closest food the quickest. The UAVs can use the same means to search an area with one small difference.

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Instead of seeking pheromone, the UAVs are repelled by it. As an area is searched, there is a pheromone trail left on a memory map common to the UAVs. Areas of high pheromone concentration indicate recent search activity. UAVs are driven to look for areas of low pheromone thereby constantly moving throughout the map seeking to update weak and decaying pheromone levels. Add some global rules to the influence of low pheromone areas and one person can easily manage multiple UAVs and ensure complete coverage of an AOI.

The global rule set includes the following:

- Choose a random AOI location for an initial position for each UAV
- Stay within the AOI
- Do not occupy the same area with more than one UAV
- For any one Point of Interest (POI) or Target of Interest (TOI) only one UAV orbits it at a time
- UAV are drawn to low levels of pheromone
- Visit all areas with zero pheromone before revisiting other areas
- If there is a tie in pheromone weighting for the next step, randomly choose from among the candidates
- The area a UAV is in now may not be the same as any area it visited during the last 2 time steps
- Move continuously unless trained on a point of interest

Bending rules

- UAVs may visit recent grids in order to stay in bounds
- UAVs may stay in one position if other positions are occupied by other UAVs

3) **Simulation.** Develop a simulation to test the behavior associated with the pheromone method of UAV collaboration. Add threat acquisition and ID tasks to determine if payload operators, still a necessary part of the system, benefit from the semi-autonomous capability to filter unimportant information.

Results Thus far, the results from simulation have been very positive. The UAVs, depending on the rate of decay and influence of distant pheromone levels, seem to sufficiently cover a large area without any input beyond the global rule set. They, within their group, are able to search and deconflict the airspace without any extraneous input.

There is more to be done. We must determine which tasks are best suited for the SASC UAVs. Doctrinal tasks can be laid over the global rule set for different types of missions. This serves the user well as it minimizes input to a doctrinal mission, location, and time. The UAS can figure out the rest.

SASC UAS provide non-subject matter experts with the ability to use and control UAVs in support of their mission. This control enhances situational awareness with relevant and timely intelligence. Complementary systems like Fire Scout and the Warfighter Information Network-Tactical (WIN-T) can act as the backbone of the SASC UAS system design.

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1 Introduction

Operations Enduring Freedom (OEF) and Iraqi Freedom (OIF) have presented intelligence and information dissemination challenges at every level. In an effort to adapt to the asymmetric operational environment (OE), US Forces have capitalized on a number of technologies that were in their nascent stages at the beginning of the Global War on Terror; specifically, tools that enhance command efforts to improve situational awareness (SA), construct and maintain a common operational picture (COP), and empower small unit leaders (SUL), at company level and below, with real-time intelligence in a varied and unpredictable environment.

In theater, operational trends seem to be extremely localized and depend on a variety of known and unknown factors. This drives the need for intelligence that is specifically tailored for unit leaders at all levels. This need is dynamic. It is a function of location and time. The proliferation of Unmanned Aerial Vehicles (UAV) deployment and operations since 2001 can be attributed to the Army's goal to provide relevant information to consumers at all levels in order to better inform the situation, mitigate risk, and set up leaders with opportunities to make better decisions quickly. Efforts to streamline and generate best practices for intelligence systems such as Predator, Raven, Shadow, and Warrior include organizations like Task Force ODIN¹. The intent is to quickly drive

information to the correct consumer through central management of resources. There are varying degrees of success. Current UAV intelligence collection practices are limited by how well the UAV Ground Control Station (GCS) personnel can interpret and deliver information to the right unit within the command they support.

The primary Army Tactical UAV (TUAV) operators, Military Occupation Specialty (MOS) 15W, are just that, UAV operators. They are not afforded the luxury of the supported units' operational focus. 15Ws are subject matter experts on the systems they operate and have ample opportunity to employ them in support of operations world wide. As of 2007, UAVs had logged over 375,000 hours with 130,000 sorties in support of both OEF and OIF. However, their ability to assist SULs can be impaired by the long and sometimes indirect link that between the information consumer and the UAV operator. Information relevant to the SUL may not seem relevant to the entire informational chain resulting in lost opportunity or expired value.

As an improvement to the system, maneuver units are collocating UAS Control systems with Brigade Combat Team (BCT) and Battalion and Squadron Tactical Operations Centers (TOCs) in order to speed responsiveness and improve the unity of effort. TF ODIN is a prime example. However, more improvements can be made in the future force giving tactical leaders and other intelligence consumers the ability to directly request and interact with UAVs. These personnel will not be MOS-trained UAV operators. Rather, they will be SULs executing tasks within a combined arms team who need clarity on a situation. With the help of the ever important GCS, SULs will be able to request, task, and dynamically reallocate multiple UAVs. This system will allow SULs to focus on their primary mission and receive tailored feedback from the UAVs. That feedback will drive better decisions and improve tactical operations. A key to this new employment of UAVs is the use of semi-autonomous and self-organizing (SASO) UAVs.

¹ Task Force (TF) ODIN (Observe, Detect, Identify, and Neutralize) is the first consolidated unit of Reconnaissance, Surveillance, Targeting and Acquisition (RSTA) operations in support of the Counter-Improvised Explosive Device (C-IED) fight in Operation Iraqi Freedom (OIF) using manned and unmanned aerial platforms. Rapidly organized, manned, and then deployed from Fort Hood, Texas, in October 2007, TF ODIN is a high-priority Army Vice Chief of Staff initiative, driven by the critical requirement to "win back the roads" using Army Aviation assets to maintain a persistent stare over demonstrated at-risk areas for IEDs. This unique Aviation task force brings together several new technologies and non-standard airframes to create synergy in the C-IED fight throughout the OIF battlespace, MNC-I. "Using Innovative Technology to Support Ground Forces" by Col. A.T. Ball and Lt. Col. Berrien T. McCutchen Jr. <http://newsblaze.com/story/20070920182734tsop.nb/topstory.html> 16 NOV 2007

2 Background

UAVs continue to demonstrate their value as a combat multiplier through the range of military operations. Currently the Army employs 4 systems: the MQ-1 Predator, RQ-5 Hunter, RQ-7 Shadow, and RQ-11 Raven (Department of Defense, 2007), Figure 1. They operate across a spectrum of performance with assorted payloads, but they are usually employed in a similar manner for intelligence collection.

Each UAS has a Launch and Recovery System (LRS), Ground Control Station (GCS) and dedicated MOS-trained Soldier that operate the payload, control the airframe, initially interpret the transmitted data feed. While the LRS is located at an airstrip, the GCS can be located elsewhere within the battle space. The LRS “hands over” the UAV to the GCS and the mission begins (Department of the Army, 2006a).

The soldiers within the GCS control the UAV and its payload. UAV position as well as information feeds from the payload are sent to another 15W with a communications link to the GCS and a Remote Viewing Terminal (RVT). The RVT is co-located with a commander’s Tactical Operations Center (TOC) in order to maximize integration of the information from the UAV and to facilitate coordinated resourcing and effort. Relevant information obtained from the UAV is then sent down to appropriate maneuver elements within the command in order to enhance their Situation Awareness (SA). Typically, any request for support is relayed from the TOC back to the GCS via voice and other information systems. Adjustments, additional requests, updates, or new information is then relayed via the same chain, Figure 2 (Department of the Army, 2006a).

This array works well for long-standing, entrenched operations, predicable schedules, and deliberate planning. However, the mission request procedure can be long and time consuming with multiple levels of approval needed to approve a request for a SUL. In many environments the SUL is best able to interpret local information as relevant and also has the most dynamic needs. The current UAS employment meth-

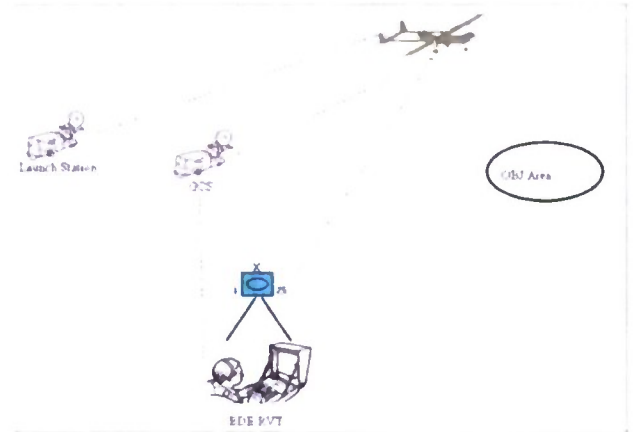
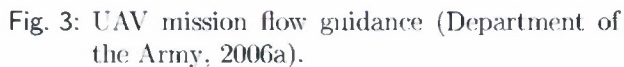


Fig. 2: UAS subsystem locations.

ods are unable to regularly support SULs without extensive preparation and planning thereby potentially missing important and actionable intelligence. Figure 4 demonstrates the current approval method for UAV mission support.

Motivated to provide faster and more relevant information from UAVs to SULs, alternative methods to request and employ UAVs must be explored. Through leveraged technology and alternative UAV control methods, a SUL can and will more directly control UAVs gaining the power to tailor and dynamically retask UAVs as necessary with fewer intermediary steps. This will yield better and faster information collection.

The Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) Unmanned Systems Office looks beyond next the generation unmanned systems to determine what capabilities and systems may become a viable part of operations in the future. AMRDEC’s mission is “To plan, manage and conduct research, exploratory and advanced development, and provide one-stop life cycle engineering, technical, and scientific support for aviation and missile weapon systems and their support systems, UAV platforms, robotic ground vehicles, and all other assigned systems, programs and projects (Aviation and Missile Research, Development and Engineering Center, 2008).”



“Unmanned systems are highly desired by combatant commanders (COCOMs) for the many roles these systems can fulfill. Tasks such as mine detection; signals intelligence; precision target designation; chemical, biological, radiological, nuclear, explosive (CBRNE) reconnaissance; and communications and data relay rank high among the COCOMs’ interests. These unmanned capabilities have helped reduce the complexity and time lag in the “sensor” component of the sensor-to-shooter chain for prosecuting “actionable intelligence. . . . Current unmanned capabilities must evolve into the future DoD acquisition and operational vision. (Department of Defense, 2007)”

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given enhancement and integration that is on the horizon. DOD has charged its acquisition managers and agencies to accelerate development and fielding by providing guidance about the most urgent needs and goals to meet them (Department of Defense, 2007).

- Goal 1. Improve the effectiveness of COCOM and coalition unmanned systems through improved integration and Joint Services collaboration.
- Goal 2. Emphasize commonality to achieve greater interoperability among system controls, communications, data products, and data links on unmanned systems.
- Goal 3. Foster the development of policies, standards, and procedures that enable safe and timely operations and the effective integration of manned and unmanned systems.
- Goal 4. Implement standardized and protected positive control measures for unmanned systems and their associated armament.
- Goal 5. Support rapid demonstration and integration of validated combat capabilities in fielded/deployed systems through a more flexible prototyping, test and logistical support process.
- Goal 6. Aggressively control cost by utilizing competition, refining and prioritizing requirements, and increasing interdependencies (networking) among DOD systems.

Based on anticipated advancements of network-centric operations, data transmission, stealth capability, and computational power, AMRDEC wants to maximize the UAV's effectiveness two ways. They want to minimize the sensor to consumer chain in order reduce relevant information loss. In addition, they want to empower SULs by giving them limited control and tasking authority over multiple UAVs.

How do we define levels of autonomy? A good place to begin is the UAV Tactical Control System (TCS) levels of control. The TCS is a scalable Advanced

Concept Technology Demonstration (ACTD) that is also interoperable and incorporates the technical interfaces necessary for the dissemination of UAV imagery and data to 24 selected joint and Service C4I systems. The TCS is designed with the capability to be configured to meet the user's deployability or operator limitations (United States Department of the Navy Research, Development and Acquisition Office, 2008).

- Level 1. Receipt and transmission of secondary imagery or data
- Level 2. Receipt of imagery or data directly from the UAV
- Level 3. Control of the UAV payload
- Level 4. Control of the UAV, less takeoff and landing
- Level 5. Full function and control of the UAV to include takeoff and landing

A GCS operator has level 5 UAV control. AMRDEC's aim is to provide SULs control at levels 2-4. This is problematic. There is a large gap to bridge in order to provide control and tailored information directly to SULs from multiple UAVs. There is currently no safe and reliable method for one Soldier to control and interpret sensor data from more than one UAV. Current UAS are designed and employed 1:1, GCS to UAV.

The Army OneSystem Common GCS will soon provide the hardware to control up to four UAVs at one time. Its fielding complies with DoD Directive (DoD) 5000.1 that establishes the requirement to acquire systems and families of systems that are interoperable (Department of Defense, 2003). It is an upgrade of the current Army GCS. It offers connectivity and control of all Army UAVs as well as vehicles from the US Navy, Marines, Air Force, and Coast Guard. In addition, it features automated take off and landing. OneSystem's system is a stepping off point for multi-UAV control, Figure 4.



Fig. 4: One System Common Ground Control Station.

Multi-UAV control by one GCS can improve intelligence collection. It would greatly expand the number of areas that one GCS is responsible for. Conversely, it could also provide greater detail and more accurate information about small areas. However in the current configuration, the responsibilities of the UAV operation would quickly overwhelm the 15Ws. A study conducted by Army Research Laboratory (ARL) showed that operators that controlled more than one UAV were promptly rendered ineffective. Both directing the UAVs and interpreting their feeds have their own unique challenges. The controller must properly space the UAVs, visit assigned Target Areas of Interest (TAIs), cover assigned AOs, avoid hazards, deconflict airspace, and rapidly react to changes in the environment. The payload operator constantly scans, controls, and interprets the payload feeds. It is nearly impossible for the GCS crew to employ only two UAVs effectively. This puts both the UAVs and the mission at severe risk of failure (Pomranky and Wojciechowski, 2007). Without a significant amount of autonomous behavior, well beyond today's levels, it is unlikely that any Soldier could safely and effectively control more than one UAV. The gap is even wider considering AMRDEC's vision

that Soldiers with MOS other than 15W gain access to multiple UAVs.

GCS technological improvements cannot completely solve the 15W's woes. The UAV operator's duties could be automated to ensure that their workload is feasible. The payload operator will likely still be the key mechanism in target identification. It will be necessary to minimize their role in the targeting process, but it will never be eliminated.

In addition, only the 15Ws in the current force are skilled enough to control UAVs. There is no opportunity for Soldiers of another MOS to control a UAV and effectively execute other tasks. Current doctrine, operations, training, material, and software do not present an effective solution for multi-UAV employment by one soldier. This is motivation for the AMRDEC effort to build advanced capabilities in UAS.

3 The Problem

Though the current OE is saturated with UAVs, it is likely that key information is missed or ignored due to centralized employment of UAS. Given the

varied information needs of SULs within a command, it is very difficult task for higher headquarters and their staffs to determine relevant intelligence for its subordinates.

3.1 Objective

The objective of the study is to create a methodology to provide, using multiple UAVs, a better and more relevant intelligence picture to SULs that does not necessitate a great deal of additional training or equipment in order to interact with the UAS.

3.2 Assumptions

- Common GCS by fielded by 2011
- UAV Airframe will evolve with enhanced processing and functionality
- FCS Common information backbone, Warrior Information Network – Tactical (WIN-T), fielded by 2013²

² The Warfighter Information Network-Tactical (WIN-T) is Army XXI's tactical telecommunications system consisting of communication infrastructure and network components from the maneuver battalion to the theater rear boundary. The WIN-T network provides command, control, communications, computers, intelligence, surveillance and reconnaissance (C4ISR) support capabilities that are mobile, secure, survivable, seamless, and capable of supporting multimedia tactical information systems within the warfighters' battlespace.

WIN-T supports unit task organization and real-time reorganization of battlefield support elements. This ability is a vital enabler for Army 2010 and Beyond operational concepts. The WIN-T network allows all Army commanders, and other communications network users, at all echelons, to exchange information internal and external to the theater, from wired or wireless telephones, computers (Internet like capability) or from video terminals.

Warfighter and signal units employ their organic WIN-T systems to integrate wide and local area battlefield networks into a commercial information technologies-based tactical network. WIN-T connects all users from theater to the maneuver battalion, to joint and multinational elements, and to the Defense Information System Network (DISN). WIN-T employs a combination of terrestrial, airborne, and satellite-based transport options, to provide robust connectivity. WIN-T will exploit the Global Information Grid (GIG) to allow worldwide connectivity. Defense Update, "WIN-T – Warfighter's Information

- SASO UAV mission set limited to intelligence collection missions
- Target Acquisition will have automated and manual components
- Airspace deconfliction will be semi-automated and informed by WIN-T
- SUL will provide waypoints, TAIs, AIs, and doctrinal tasks to SASO UAVs

3.3 Definitions

Swarm Behavior: Self-organizing behavior among a group of entities that achieves or attempts to achieve a common goal.

Self-Organizing Behavior: Coordinated behavior by a group of entities with a common goal that requires little or no direction from a central authority. This behavior manifests as specific tasks for each individual that can dynamically adjust with changes in the environment.

Semi-Autonomous Behavior: Behavior of a system (machine) which interacts intelligently with a human user (collaborator) who might command, modify, or override its behavior (Tahboub, 2001). Autonomous behavior is framed by user's capabilities and needs.

Target Acquisition: The detection, identification, and location of a target in sufficient detail to permit the effective employment of weapons (Department of the Army, 2004).

3.4 Stakeholder Analysis

Stakeholder analysis consisted of interviews and input derived from persons and agencies directly involved with the design, acquisition, and operation of UAS using notes, surveys, and anecdotes. The future of UAS within DoD is clear given the preponderance of research, literature, acquisition, operations, field and technical manuals, and the biannual

Network – Tactical," November 2008. <http://www.defense-update.com/products/w/win-t.htm>.

UAS Roadmap from the Office of the Secretary of Defense (OSD). In sum, they all agree that 1) UAS will see more incorporation over the long term and 2) increased automation within UAVs would be greatly beneficial to strategy, operations, and tactics.

Looking at system stakeholders within the construct of the Systems Design Process (SDP) developed by faculty of the United States Military Academy (USMA) Department of Systems Engineering, they can be broken down into three distinct categories, sponsor or program manager, customer, and user (Parnell et al., 2008). The program manager is responsible for the overall design and implementation of the system. They typically would initiate the effort for a system design. The customer is responsible to acquire and support the system for their organization. Finally, the user will operate the system once it is fielded (Parnell et al., 2008).

In this instance, the AMRDEC Unmanned Systems Office (USO) serves as the study sponsor as this effort relates to future UAV concepts. The Program Manager (PM) for UAS is the customer, and UAV operators, SULs, and other intelligence consumers are the users.

AMRDEC USO was very clear about their desires. They desired a UAS that allows SULs with MOS other than 15W to gain some level of control over multiple UAVs in order to augment mission requirements. There should be an interface for the SUL to directly interface with and exercise some level of control of the UAVs. The system should not burden the SUL and should enhance, not detract from, their immediate mission. Mr. Paul Dinardo from the AMRDEC UAS Future Systems branch indicated that there was no expectation to implement the system prior to FCS fielding. In addition, he asked that insect-like swarming behaviors be investigated as a possible means to reducing the multi-UAV mission workload for both 15Ws and SULs.

PM UAS was not looking quite so far into the future. They field, support, and upgrade current UAS within the Army and are not looking past FCS as of yet. Their main concern was that any system be robust and jointly interoperable, and that second and third

order effects of fielding such a system be addressed, such as the information dissemination, airspace coordination, responsibility for the UAVs aloft, UAV allocation within the battle space, though not all such effects are within the purview of this study.

UAV operators with varied levels of total flight time (600-2000 hours) including time flown in support of OIF or OEF were asked both formally and informally, face to face, and via electronic mail to answer questions to help drive the development of autonomous features in Army UAVs. As a group, their experience included all current Army UAVs.

They were asked which GCS tasks they would automate. With respect to advancements in autonomous behavior, users requested obstacle avoidance and anti-collision capabilities along with automatic airspace deconfliction, landings, and launches.

The 15Ws were also asked about the ease of controlling multiple UAVs. Given prescribed and preplanned routes within an AO, they felt that control would not be an issue. However, they would have very little freedom to execute dynamic retasking without long response times due to involved mission planning. They did not think that multiple UAVs could be controlled by one operator. The AO coverage, airspace deconfliction and interpretation of multiple payload feeds is too difficult for multiple UAVs. It is unlikely that one payload operator will successfully be able to view and analyze more than one payload feed without highly advanced target acquisition technology. They did not anticipate any technology that could replicate the Soldier's ability to conduct unique target identification.

Intelligence consumer feed back was consistent. Users of UAV information video and data feeds wanted a simple and accurate system. MAJ John Rude, Executive Office of the 1st Infantry Division Combat Aviation Brigade (CAB) summed it up this way, "UAVs are providing us with much more capability than we have had in the past. They dramatically increase our ability to observe the area of responsibility, and the more we are able to see, the better we are able to do our job. Unmanned systems, including Hunter, are tightening the kill chain. (Howard, 2008)"

3.5 Functional Analysis

The stakeholders needs did not conflict. Though the study is limited in its ability to treat all of PM UAS interests in depth, there was sufficient information to confidently move forward with a functional hierarchy that captured the stakeholders' needs, Figure 5. However, the far time horizon until physical implementation, anticipated technology gaps, and exploratory nature of the study prevented comprehensive development of value modeling.

The functional analysis demonstrates the enormity of the design task at hand. Since the system design and the basic behaviors of SASO UAVs are not yet defined, the scope of the study will be limited to their development and demonstration. It will include a proposed methodology to program SASO behaviors in multiple UAVs with limited input from a directly supported agent. Implementation of SASO rule sets will be initially validated within a proof of concept simulation. The design will also include a construct for implementation of SASO within tactical operations for SULs.

4 Proposed System Design

Assume that an Infantry SUL is on a mission and needs to improve his intelligence picture about a large AO. The SUL would contact the TOC and request support. Given little existing information about the AO, The TOC could allocate SASO UAVs to cover the large area quickly and minimize the intelligence collection burden on both the TOC and the Soldier.

After only brief mission planning (primarily enroute flight planning) by a 15W, SASO UAVs would launch under GCS control from a BCT's repository of unassigned UAVs. The few that are chosen to help the Soldier are given the coordinates of the AO, an initial doctrinal tasking, and a list of items to target. The SUL's new recon element forms a loose network in order to collaborate and travels to the AO.

Upon arriving at the AO UAVs check in with the SUL to confirm the mission and target list. The SUL

uses a handheld device like a Personal Data Assistant (PDA) or a voice activation system like Microsoft Sync³, to link up and interface with the UAVs. The interface gives the SUL predefined menus to rapidly task the SASO UAVs. It also provides the SUL a link back to the GCS for support with target identification or other nonstandard tasks. Working over WIN-T, the TOC and other agencies will have access to any intelligence generated by the mission.

The interface tool contains a list of tasks to choose from such as area, route, or zone reconnaissance and selectable targets such as land features and buildings by type or vehicles and persons by general description or behavior. After receiving their task, the UAVs, without any other instructions, fan out over the assigned area and begin. In the mean time, the SUL is able to get back to the task at hand. When one or more UAVs spot an item of interest, they orbit it and contact the Soldier awaiting further instructions. Meanwhile, the other SASO UAVs automatically reorganize to search the remainder of the AO. The SUL makes a determination of what to do from there. This target recognition functionality is a key element as it alleviates both the SUL and GCS payload operators from having to constantly stare at UAV feeds thereby preventing them from doing anything else. Though this system is complex, the UAV behavior can managed with a few simple rules inspired by Mother Nature.

4.1 Swarming Behaviors

SASO UAS use collaborative behavior. Developing it within the UAVs was the primary task. With this in mind, I examined systems of social entities, specifically insects and animals. I was looking for systems where individual entities had little or no idea about the aggregate workings and goals of the whole and where complete control over the total population did not exist. I wanted systems where only groups of

³ Microsoft Sync™ is a voice activated in-car communications systems currently available in Ford, Lincoln, Mercury products. Its technology allows vehicle drivers to operate a number of music players and communications devices. www.syncmyride.com/#/overlay/overlay_what_is_sync

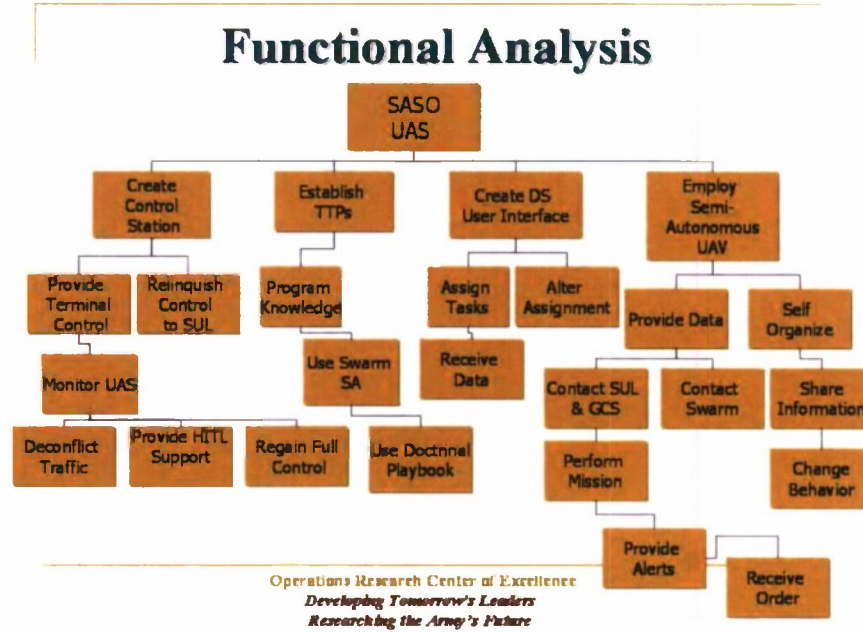


Fig. 5: SASO UAV functional analysis.

skilled or preprogrammed entities could achieve goals and where the success or failure of any one entity was irrelevant. SASO UAVs will not have a global operating picture and they must work in concert with other UAVs to complete their intelligence collection.

After considering a number of communities, I modeled the SASO UAV behavior on that encountered in most ant colonies. Due to their ubiquitous nature and ordered colonies, ants have been studied and modeled through out the millennia. Their methods have been used as a heuristic to solve traveling salesman problems, optimize pricing, and design robot hardware and software (Sleigh, 2003). Ant colony behavior demonstrates great potential for the development of SASO UAVs.

The term “army of ants” is a misnomer. Ants, with up to 2 million members in a colony, do not operate in accordance with the traditional military model. All operations (security, food gathering, construction, care of larva, etc.) are conducted without any central control. Each ant colony each has a queen.

But, she does not send out orders to her minions with a grand intent for the colony. In fact, her role is basically limited to breeding more workers. Ants are born with a skill set and exist to play their role, like nurse, worker, or security. Ants interact with the environment then transmit significant information back to the colony in the form of individual contact that elicits changes in behavior. As information is propagated, the colony reacts (Sleigh, 2003). An ant is insignificant. Grouped together they can take noticeable action.

Ant colonies do share some traits with the military. Ants, like Soldiers, have specific jobs, communicate with others, and are intelligent beings. Ants each have an MOS. Within each MOS, ants are programmed with 20 to 40 behaviors and faithfully execute their tasks. Though not directed to specific individuals, ants communicate using 10 to 20 chemical pheromones to transmit requests, warnings, and status. Within the insect world, ants have exceptionally large brains. It has been proposed that the individ-



Fig. 6: Ant pheromones optimize colony food search.

ual ant has the same capacity to information as the Macintosh II computer (Sleigh, 2003).

The preprogrammed tasks and pheromone communication methods of ants form the basis of SOSA behavior in UAVs. Each morning foraging ants leave the colony to look for food. They are motivated by inputs like increasing sunlight and signals from the colony about the number of larvae on hand. Naturally, they search for food stores close to their colony first and leave a trail of pheromones in their wake. When an ant finds a food source, it traverses back and forth from the food to the colony with its treasure. This concentrates the pheromone. Other ants sense high levels of pheromone along the successful ant's trail and are drawn to it. They too find food inadvertently strengthening the scent of the trail. This continues until the source is exhausted or the colony's stores are full. Without trying, ants are optimizers. They are able to get the closest food, the quickest, Figure 6 (Sleigh, 2003).

The SASO UAVs can use the same means to conduct a coordinated search of an area with one small difference. Instead of seeking pheromone, the SASO UAVs are repelled by it. As an area is searched, each UAV leaves its own trail of pheromone. Of course it's infeasible to use real pheromone. Instead, all of the UAVs track the pheromone trails share a common memory

map, presumably through WIN-T. Areas of higher pheromone concentration indicate recent search activity. UAVs seek areas of low pheromone thereby constantly moving throughout the map. They seek to update weak and decaying pheromone levels while providing intelligence to the SUL. Once the base behaviors for SASO are programmed in the UAVs, doctrinal tasks and other requests can be layered on top. Doing so allows one person to easily manage multiple UAVs and ensure complete coverage of an AO with very little other specific guidance for the UAVs.

4.2 SASO UAS System Design

SASO UAS allow for a restructuring of traditional UAS employment as their behavior can increase intelligence collection opportunities for SULs in real time. The system design is an excursion from today's UAS operations. Beginning with hardware, the GCS is still the central node for launch, recovery, and Level 5 control of any UAS. However, instead of distributing small UAV units through out Corps and BCTs, SASO UAVs are pooled; ready to support SULs. The pool of SASO UAVs is then assigned to support subordinate units within a BCT in a similar fashion to priority of fires in a fire support plan. Based on the operational plan, direct support (DS) and general support (GS) relationships will be established with the subordinate units. Further partitioning will be at commanders' discretion. SULs can then request SASO UAV intelligence support, Figure 7.

SULs will request support through their organic command and control systems with interfaces designed to interact with the GCS, their TOC, and the SASO UAVs. The interface will have a menu of doctrinal tasks to choose from. It will query the SUL, also known as the direct support agent, about the geographic area, time frame, and purpose of the search. For instance, the SUL could ask for a route recon, provide the limits of the search, the required completion time, and choose from a list of specific features of interest.

- The SASO UAV's basic rule set includes the following:

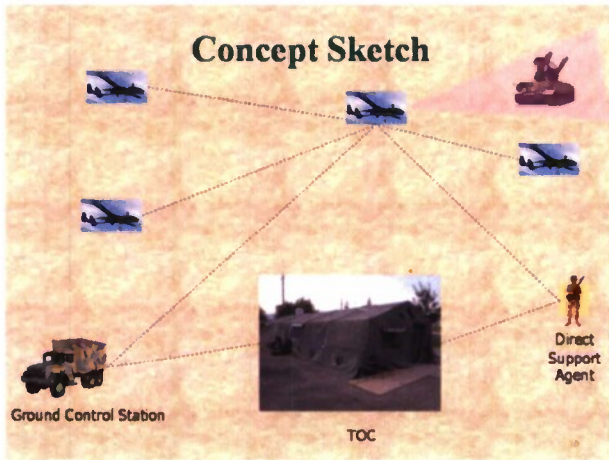


Fig. 7: SASO system employment.

- Choose a random AO location for an initial position for each UAV.
- Stay within the assigned AO.
- Do not occupy the same area with more than one UAV.
- For any one Point of Interest (POI) or Target of Interest (TOI) only one UAV orbits it at a time.
- UAV are drawn to low levels of pheromone.
- Visit all areas with zero pheromone before visiting other areas.
- If there is a tie in pheromone weighting for the next step, randomly choose from among the candidates.
- The area a UAV is in now may not be the same as any area it visited in its last two moves.
- Move continuously unless trained on a point of interest.

In case of conflict caused by the initial rule set, the following rules allow a relaxation to ensure the mission can continue.

- UAVs may visit recent grids in order to stay in bounds.
- UAVs may stay in one position if all other available positions are occupied by other UAVs.

The true power of SASO UAS is the ability to layer the doctrinal tasks on top of the base SASO behavior. Assuming the SUL assigns a doctrinal task from a predefined menu, each UAV will know exactly what to do. For example, tasks associated with a route reconnaissance as outlined in FM 17-95 Cavalry Operations (Department of the Army, 1996) are found below.

- Reconnoiter and determine the trafficability of the route.
- Reconnoiter all terrain the enemy can use to dominate movement along the route.
- Reconnoiter all built-up areas along the route.
- Reconnoiter all lateral routes.
- Inspect and evaluate all bridges on the route.
- Locate fords or crossing sites near all bridges on the route.
- Inspect and evaluate all overpasses, underpasses, and culverts.
- Reconnoiter all defiles along the route. Clear all defiles of enemy and obstacles within capability or locate a bypass.
- Locate and clear the route of mines, obstacles, and barriers within capability.
- Locate a bypass around built-up areas, obstacles, and contaminated areas.
- Find and report all enemy that can influence movement along the route.
- Report route information.

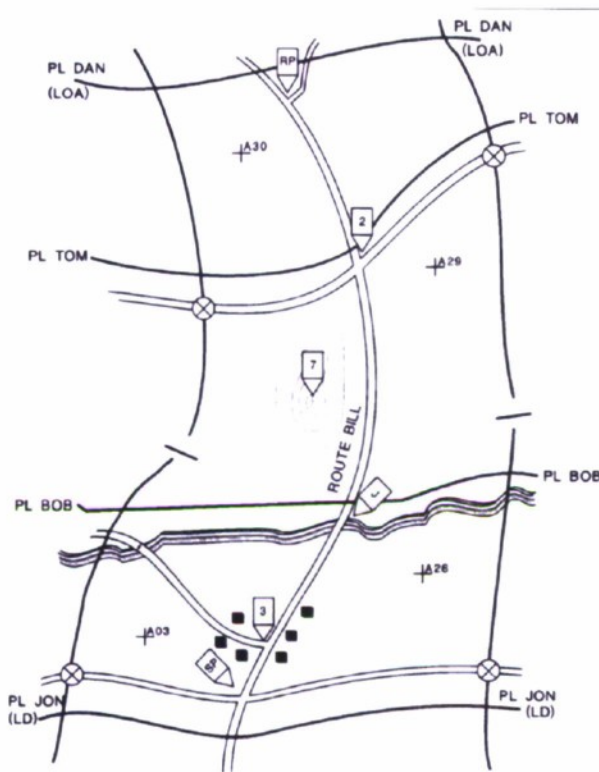


Fig. 8: Route recon plan. (Department of the Army, 1996)

Providing the SUL with an array of doctrinal reconnaissance missions to select from is critical. It allows the SUL to quickly and succinctly communicate with the GCS so the appropriate number and type of UAVs can be assigned. In addition, the UAVs will arrive in the AO prepared to execute taskings. Their swarming behavior will ensure sufficient coverage within the AO and allow for control by only one person. The GCS will ensure the UAVs arrive at the appropriate AO. The SASO UAVs will not receive mission tasking from the GCS once in the AO. The SUL will be able to dynamically retask the UAVs as necessary through the communications device but will not have more than level 3 control, control of the UAV payload.

The tailorable target list, along with the doctrinal task, acts as input for any advanced visual target filtering and acquisition. Without filtering, it is impossible for the SUL to complete his primary mission and efficiently interpret the payload feeds. This is also true for the operators in the GCS. It is likely that advancements will be made in both optics and software to reduce the burden associated with target acquisition. That leads back to the tailored target list. It can be used as a cue for target location.

For instance, TC 1-228, the Aircrew Training Manual for the OH-58 A/C Observation Helicopter, delineates tasks for aeroscout pilots. Task 1472, Perform Aerial Observation, identifies visual cues to improve searches (Department of the Army, 2006b). In areas where natural cover and concealment make detection difficult, visual cues may indicate enemy activity. Some of these cues are as follows:

- **Color.** Colors in nature tend to be subdued. Look for colors that stand out against, and contrast with, natural backdrops.
- **Texture.** Smooth surfaces, such as glass windows or canopies, will shine when reflecting light. Rough surfaces will not.
- **Shadows.** Man-made objects cast distinctive shadows characterized by regular shapes and contours, as opposed to the random patterns that occur naturally.

- Trails. Trails leading into an area should be observed for cues as to the type and quantity of traffic, and how recently it passed.
- Smoke. Smoke should be observed for color, smell, and volume.
- Movement and light. The most easily detectable sign of enemy activity is movement and, at night, light. Movement may include disturbance of foliage, snow, soil, or birds.
- Obvious sightings. The enemy is skillful in the art of camouflage. The Pilot/Copilot must be aware that obvious sightings may be intentional because of high concentrations of antiaircraft weapons.

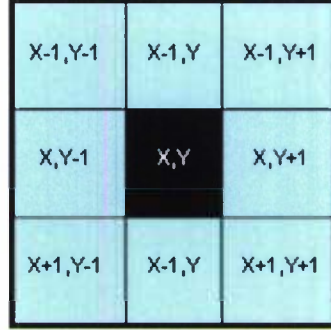


Fig. 9: Local neighborhood segmented by payload viewing area.

5 Modeling SASO Behavior Rule Sets

The mathematical model for the SASO pheromone-driven movement for UAVs is based on decaying functions that represent pheromone levels on a grid overlay on the AO. Each subgrid is a square that approximates the area that a visual payload can view at a discrete point in time, 50m x 50m as an approximation. The continuous movement of the UAVs is represented with a discrete event model and simulation. The interstitial time between steps is the time it takes for a UAV flying at a given constant speed to move from a viewed square to the next unviewed square on the grid, about 3 seconds per step.

Given a position within an AOI (x,y at time t), a single UAV typically can choose from 8 grid squares for its next step, Figure 9. This set of grid squares is called the local neighborhood. The choice is primarily driven by the pheromone states. It is a manifestation of the UAV's mission to cover the AOI updating the memory map by marking its travels with pheromones. Other rules that govern the UAV's movement are functions of airspace deconfliction and other mission specific tasks.

For the AO, let $P_{ij}(t)$ be the pheromone level in position ij at time t where $i \in [X]$, $j \in [Y]$. Pheromones are at a maximum (1) when a UAV visits the

grid. At the next time step, decay begins $p_{ij}(t) = N_0 e^{-\lambda t}$, $N \in [0, 1]$. The levels within the grid squares, weights, w_{ij} , are exclusively determined by the pheromone level at every point except within the local neighborhood, $w_{ij}(t) = p_{ij}(t)$. Note that $p_{ij}(t) = 0, \forall i, j, t$ until initially viewed by a UAV. Once viewed by the UAV, $p_{ij}(t) = 1$ then the decay begins. For the remainder of the simulation, the UAV movement will update sensor grid square pheromone values to 1 each time they pass overhead.

It is necessary to look beyond the local neighborhood to move the UAV to areas with no or extremely low pheromone levels. A solution is to modify the pheromone levels of the local neighborhood choices, $w_{ij}(t) \neq p_{ij}(t)$ rather $w_{ij}(t) = p_{ij}(t) \cdot f(AO p_{ij}(t))$. Where $f(AO p_{ij}(t))$ is a function that reflects the pheromone levels outside of the immediate local set of grid choices. The pheromone levels of the greater portions of the AO will then have some influence on the UAV's local choice. Areas of the AO that need the greatest attention will eventually receive it.

Driving UAV behavior using pheromone influence from beyond the local neighborhood is done with a method we called quadrant averaging. Given a matrix ($m \times n$), one can divide the AO into quadrants. The state of the pheromone decay within the matrix drives the motion of the UAVs as they seek to cover the AOI. The present position of the UAV, indicated in Figure 10 by the black square, has two

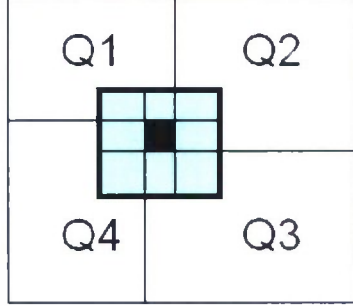


Fig. 10: AO quadrants.

pheromone neighborhoods that influence the UAV's motion, the local neighborhood, in blue, and the AOI itself. Each quadrant influences grid squares in the local neighborhood.

The levels of pheromone in the quadrants can influence the choice a UAV makes at the next time step through Quadrant Averaging. The next step should be toward areas with little or no pheromone levels. This is done by taking the simple average of the pheromone levels in each quadrant at time t , $\overline{Q_k(t)}$, $k = 1 \dots 4$. In the local neighborhood, pictured in blue above, $w_{ij}(t) = p_{ij}(t) \cdot \overline{Q_k(t)}$ where

for $i = x - 1$ and $j = y - 1, y$

$$w_{ij}(t) = p_{ij}(t) \cdot \overline{Q_1(t)}$$

$$\overline{Q_1(t)} = \frac{\sum_{a=x-1}^{x-1} \sum_{b=y-1}^y p_{ab} - \sum \sum p_{ij}}{(x-1) \cdot (y) - 2}$$

for $i = x - 1, x$ and $j = y + 1$

$$w_{ij}(t) = p_{ij}(t) \cdot \overline{Q_2(t)}$$

$$\overline{Q_2(t)} = \frac{\sum_{a=x}^{x-1} \sum_{b=y+1}^y p_{ab} - \sum \sum p_{ij}}{x \cdot (n-y) - 2}$$

for $i = x + 1$ and $j = y, y + 1$

$$w_{ij}(t) = p_{ij}(t) \cdot \overline{Q_3(t)}$$

$$\overline{Q_3(t)} = \frac{\sum_{a=x+1}^m \sum_{b=y}^y p_{ab} - \sum \sum p_{ij}}{(m-x) \cdot (n-y+1) - 2}$$

for $i = x, x + 1$ and $j = y, y + 1$

$$w_{ij}(t) = p_{ij}(t) \cdot \overline{Q_4(t)}$$

$$\overline{Q_4(t)} = \frac{\sum_{a=x}^m \sum_{b=y+1}^{y-1} p_{ab} - \sum \sum p_{ij}}{(m+x+1) \cdot (y-1) - 2}$$

The impact of the quadrant averaging is shown, Figure 11. All of the local neighborhood pheromone values in the Quadrant Averaging matrix, $w_{ij}(t) = p_{ij}(t) \cdot \overline{Q_k(t)}$ are noticeably lower than the initial memory matrix where the local area weighting based on pheromone decay alone, $w_{ij}(t) = p_{ij}(t)$.

The quadrant averages are all close to .5, as expected. However, the quadrant averaging does drive interest in Quadrant 3 due to the lower average. The basic impact of the quadrant averaging is that the local neighborhood pheromones are lower, position by position, another expected result. Since the varying degrees of the current quadrant pheromone levels are relatively uniformly distributed to appropriate cells within the local neighborhood of the UAV, the UAV chooses not only the next cell with the greatest need for pheromone but it will likely be in the direction of the quadrant of the AOI with the greatest need as well. Quadrant averaging rebalances the UAV travel within the AOI by placing various sized perturbations in the local neighborhood values that will help leave no stone unturned, again and again.

6 Proof of Concept Simulation

A federation of simulations was used to demonstrate the proof of concept for SASO UAVs. There were few simulations that provide UAVs with the necessary characteristics due to the complex nature of the communications, command and control, threat ID and classification, and control of the UAV. Rapid and detailed information exchange and well as high resolution environment and entity representation were critical the model's implementation. We programmed

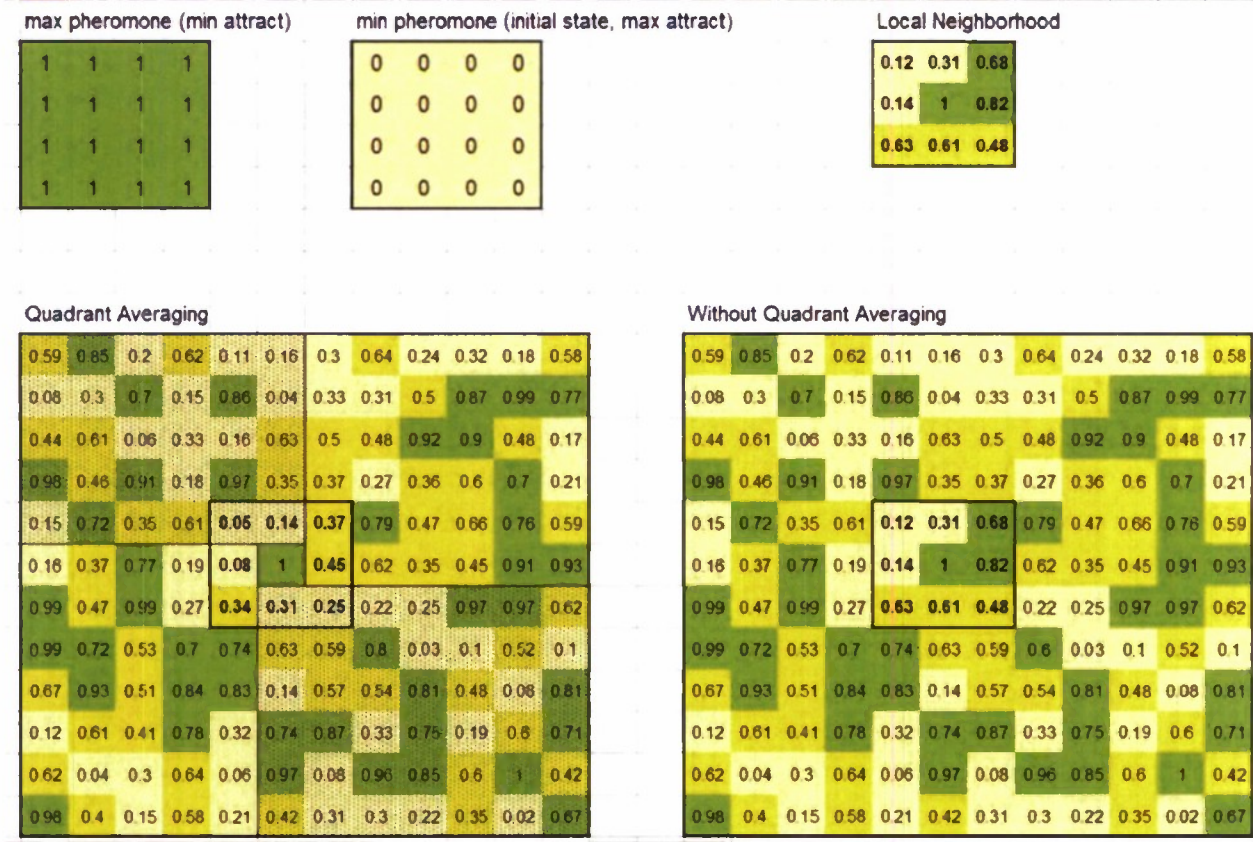


Fig. 11: Quadrant averaging and pheromone memory map.

a wide range of behaviors, both parametrically and constructively.

The federates were specifically chosen to meet the needs of the experimental question. Specifically, we were interested in how well various rule sets would generate semi-autonomous behavior in UAVs. The UAVs performed their tasks in a relatively busy operational environment, including varied terrain and friendly and enemy forces. The UAVs searched for a variety of enemy targets. We ran a SASO mission with no extraneous input to drive behavior and we counted the number of unique enemy contacts made in a specified period. As a basis of comparison, we did the same with a set of UAVs that had prescribed and deterministic routing throughout the AO, Figure 12.

Entity representation within the simulation was straightforward. The SASO UAVs, friendly, and enemy forces were all represented by VR Forces. Input for the SASO UAV behaviors were driven by messages sent using Distributed Interactive Simulation (IEEE-SA Standards Board, 1998) (DIS) bridge from a program written in Haskell. Haskell is a “non-strict” computing language with algebraic syntax whose strengths include interfacing with other program and languages (Hudak et al., 2007). It was also used to generate, update, and display the SASO UAV memory grid. VR Forces was sufficient for the force on force and other common military scenarios to include degrees of control for vehicles, weapons, aggregate formations, and tactics. VR Forces offered some artificial intelligence and decision making capabilities as well.

Data collection was a combination of ad hoc methods. The federates were not stand-alone analysis tools. They were primarily designed for training and system familiarization. We were able to document the events recording the activity across the DIS bridge. A message logger captured DIS Protocol Data Units (PDUs) broadcast from all federates. This provided a record of the events as well as a rapid and easy playback of federation exercise iterations.

In the simulation, two sets of four UAVs were alternately sent into a small AO (10 km by 10km) to con-

duct an area recon. There were a number of targets placed throughout the AO for the UAVs to observe. The first set of UAVs represented the current state of the art. They were each given deterministic and prescribed overlapping routing through the AO and flew for a fixed amount of time. The amount of time that each UAV was in visual contact with a target was recorded.

After a reset, a second set of UAVs with SASO behaviors entered the AO to also look for targets. They were given no routing other than the instructions provided by the Haskell program. They flew for the same amount of time as the first set of UAVs. The amount of time that each SASO UAV was in visual contact with a target was recorded. As their behavior was stochastic in nature, multiple iterations were run to establish a confidence interval for the amount of time the SASO UAVs spent in contact with the targets. The aim was to compare the success of the vastly different behaving sets of UAVs. The first set, with extensive human input, and the second, with none, generated very interesting results.

The control UAVs, with prescribed routing, spent 17.74% of the time in contact with targets. The SASO UAVs with stochastic and cooperative behaviors gained contact with the targets 18.62% of the time on average. The 95% confidence interval was 17.39% to 19.86%. The results between the sets of UAV types overlap and are thus statistically indistinguishable; a very respectable outcome for the SASO UAVs, Figure 13.

7 Conclusion

Though many assumptions were made in order to simulate SASO behaviors in UAVs, this effort can be looked upon as a step in the right direction for the next generation of unmanned systems. It is natural to want and demand more out of the technology as it matures. This method allows, through very simple rule sets, rapid and dynamic retasking, and hands-off behavior. It will allow any Soldier to focus on their mission yet benefit from local, tailorable intelligence

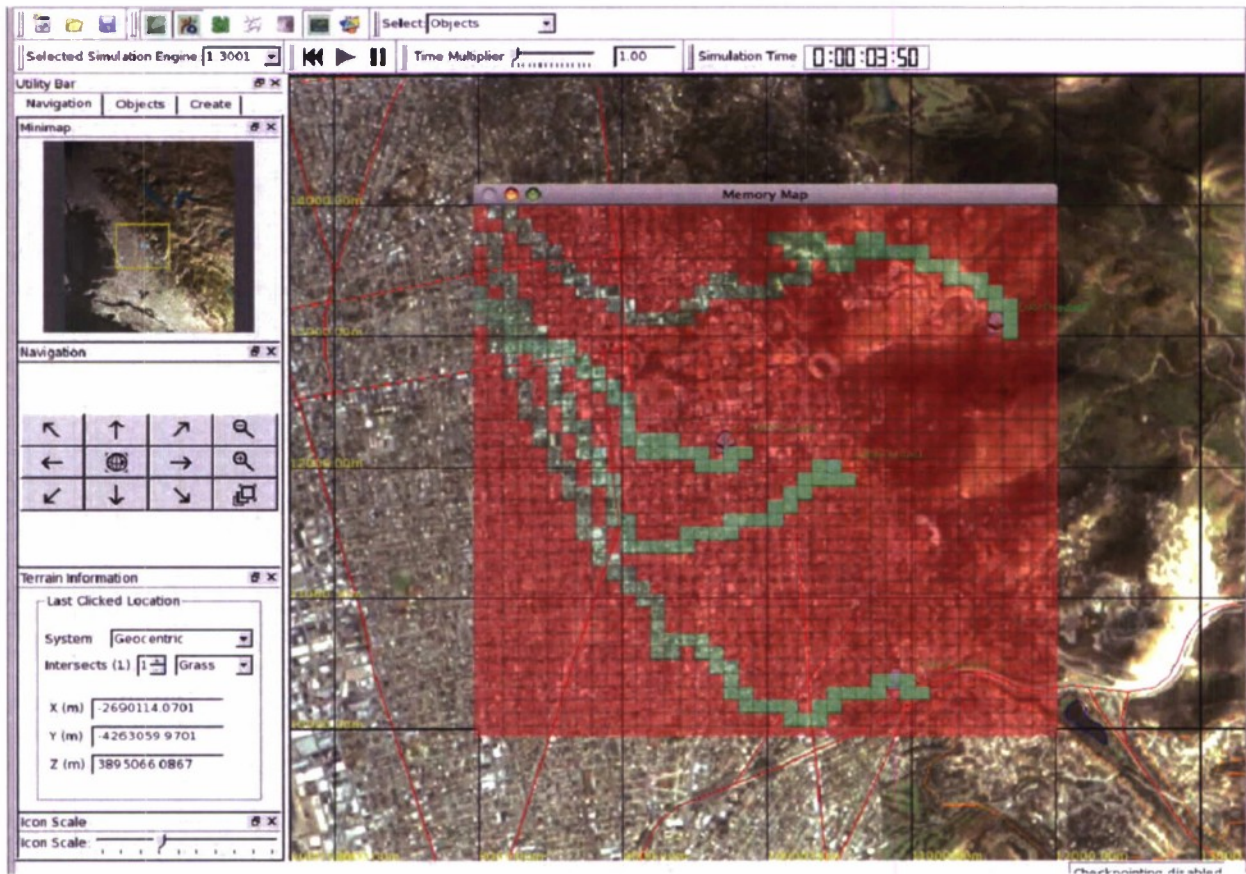


Fig. 12: Autonomous UAV federated model with embedded memory map.

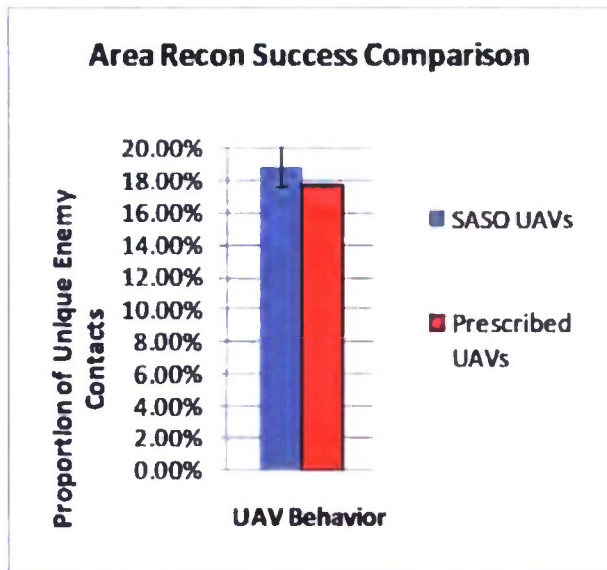


Fig. 13: Target contact, SASO vs. prescribed routing of UAVs.

viding the Soldier the best information possible.

that was once only available to dedicated UAV subject matter experts and staff cells. It could be lead to personal automated aeroscout platoons providing unencumbering support for SULs.

The rule set and biomimicry used by the SASO UAVs provides a foundation. Because it uses so few rules to achieve the SASO behaviors, it is relatively easy to change them as factors and track the behavior response. We must continue to refine the list of tasks that are best suited for the SASO UAVs. Doctrinal tasks can be laid over the global rule set for different types of missions. This serves the user well as it minimizes input to a doctrinal mission, location, and time. The UAS can figure out the rest. It paves the way for varied and more complicated missions to be layered onto the mission platform such as search and rescue, fire fighting, and possibly interdiction.

SASO UAS provide non-subject matter experts with the ability to use and control UAVs in support of their mission. This control enhances situational awareness with relevant and timely intelligence. Complementary systems like Fire Scout and the WIN-T can act as the backbone of the SASO UAS system design pro-

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Nomenclature

AMRDEC	Aviation and Missile Research Development and Engineering Center	UAS	Unmanned Aircraft Systems
AOI	Area of Interest	USMA	United States Military Academy
BCT	Brigade Combat Team	WIN-T	Warfighter Information Network - Tactical
C4ISR	Command, control, communications, computers, intelligence, surveillance, and reconnaissance		
COP	Common Operational Picture		
DIS	Distributed Interactive Simulation		
DISN	Defense Information System Network		
DS	Direct Support		
FCS	Future Combat Systems		
GS	General Support		
GWOT	Global War on Terror		
MOS	Military Occupational Specialty		
OEF	Operation Enduring Freedom		
OIF	Operation Iraqi Freedom		
OSD	Office of the Secretary of Defense		
POI	Point of Interest		
RSTA	Reconnaissance, Surveillance, and Target Acquisition		
SA	Situation Awareness		
SASC	Semi-Autonomous Self-Collaborating		
SDP	Systems Decision Process		
SUL	Small Unit Leaders		
TOC	Tactical Operations Center		
TOI	Target of Interest		
TUAV	Tactical Unmanned Aerial Vehicle		

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